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Weighted approach for multivariate analysis of variance in measurement system analysis

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ABSTRACT

In a process that is integral to a measurement system, some variation is likely to occur. Measurement system analysis is an important area of study that is able to determine the amount of variation. In evaluating a measurement system's variation, the most adequate technique, once an instrument is calibrated, is gauge repeatability and reproducibility (GR&R). For evaluating multivariate measurement systems, however, discussion has been scarce. Some researchers have applied multivariate analysis of variance to estimate the evaluation indexes; here the geometric mean is used as an agglutination strategy for the eigenvalues extracted from variance–covariance matrices. This approach, however, has some weaknesses. This paper thus proposes new multivariate indexes based on four weighted approaches. Statistical analysis of empirical and data from the literature indicates that the most effective weighting strategy in multivariate GR&R studies is based on an explanation of the percentages of the eigenvalues extracted from a measurement system' matrix.

1. Introduction

To properly monitor and improve a manufacturing process, it is necessary to measure attributes of the process's output. For any group of measurements collected for this purpose, at least part of the variation is due to the measurement system itself. This is because repeated measurements of any particular item occasionally result in different values [1–7]. To ensure that measurement system variability is not detrimentally large, it is necessary to conduct measurement system analysis (MSA). Such a study can be conducted in virtually any type of manufacturing industry. MSA helps to quantify the ability of a gauge or measuring device to produce data that supports analyst's decision-making requirements [8]. The purpose of this study is to (i) determine the amount of variability in collected data that is due to the measurement system, (ii) isolate the sources of variability in the measurement system, and (iii) assess whether the measurement system is suitable for use in a broader project or other applications [9,10]. According to He et al. [11], MSA is an important element of Six Sigma as well as of the ISO/TS 16949 standards.

The most common study in MSA to evaluate the precision of measurement systems is gauge repeatability and reproducibility (GR&R). Repeatability represents the variability from the gauge or measurement instrument when it is used to measure the same unit (with the same operator or setup or in the same time period). Reproducibility reflects the variability arising from different operators, setups, or time periods [7,10,12–17]. Some works in the literature [18–21] have used repeatability and/or reproducibility concepts; these, however, ignored GR&R statistical analysis in comparing measurement system variation to process variation. These studies involving only gauge variability are insufficient to determine whether the measurement system is able to monitor a particular manufacturing process. If variation due to the measurement system is small relative to the variation of the process, then the measurement system is deemed capable. This means the system can be used to monitor the process [9]. GR&R studies must be performed any time a process is modified. This is because as process variation decreases, a once-capable measurement system may now be incapable. Two methods commonly used in the analysis of a GR&R study are: (1) analysis of variance (ANOVA) and (2) Xbar and R chart [5,10]. Analysts prefer the ANOVA method because it measures the operator-to-part interaction gauge error—a variation not included in the Xbar and R method [4].

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Currently, the ANOVA method for GR&R studies can be applied only to univariate data [5,22]. To discriminate among products, however, manufacturers often use more than a single measurement on a single product characteristic [9]. To estimate evaluation indexes in such a GR&R study, the analyst must consider the correlation structure among the characteristics, a task more suited to multivariate methods [7]. Using automotive body panel gauge-study data, Majeske [3] demonstrated how to fit multivariate analysis of variance (MANOVA) model and estimate the evaluation indexes to multivariate measurement systems. In his analysis, it was shown that the multivariate approach had resulted in a more practical representation of the errors and led the manufacturer to approve the gauge. Wang and Yang [22] presented a GR&R study with multiple characteristics using principal component analysis (PCA). The authors pointed out that when correlated quality characteristics are present a GR&R study must be conducted carefully. In this case study, the composite indexes *P/T* (precision-to-tolerance) and *%R&R* (percentage of repeatability and reproducibility) with ANOVA method were overestimated by the PCA by 35.75% and 11.54%, respectively. Wang and Chien [5] analyzed a measurement system using a multivariate GR&R study and provided the confidence interval for two measures *P/T* and the number of distinct categories (ndc). Through a case study, the authors assessed the performance of three methods (ANOVA, PCA and POBREP—process-oriented basis representation). The authors argued that POBREP outperformed the others by being able to identify the causes of production problems. Peruchi et al. [7] proposed a multivariate GR&R method based on weighted PCA. The method was applied to experimental and simulated data to compare its performance to univariate and multivariate methods. The authors demonstrated that their weighted principal component (WPC) method was more robust than the others, considering not only several correlation structures but also distinct measurement systems.

Larsen [23] extended the univariate GR&R study to a common manufacturing test scenario where multiple characteristics were tested on each device. Illustrating with examples from an industrial application, the author showed that total yield, false failures, and missed false estimates could lead to improvements in the production test process and hence to lower production costs and, ultimately, to customers receiving higher quality products. Flynn et al. [24] used regression analysis to analyze the comparative performance capability between two functionally equivalent but technologically different automatic measurement systems. For such accurate measurements as repeatability and reproducibility, the authors found as inappropriate the “pass/fail” criteria for the unit being tested. Hence, they proposed a methodology based on PCA and MANOVA to examine whether there was a statistically significant difference among the measurement systems. He et al. [11] proposed a PCA-based approach in MSA for the in-process monitoring of all instruments in multisite testing. The approach considers a faulty instrument to be one whose statistical distribution of measurements differs significantly from the overall distribution across multiple test instruments. Their approach can be implemented as an online monitoring technique for test instruments so that, until a faulty instrument is identified, production goes uninterrupted. Parente et al. [25] applied univariate and multivariate methods to evaluate repeatability and reproducibility of the measurement of reverse phase chromatography (RP-HPLC) peptide profiles of extracts from cheddar cheese. The ability to discriminate different samples was assessed according to the sources of variability in their measurement and analysis procedure. The authors showed that their study had an important impact on the design and analysis of experiments for the profiling of cheese proteolysis. Inferential statistical techniques helped them analyze the relationships between design variables and proteolysis.

This paper focuses on multivariate analysis of variance method applied to GR&R studies (Section 2). The relevance of this topic lies in the fact that the variation of more complex measurement systems must be evaluated by more sophisticated methods. When multiple correlated characteristics are being monitored, multivariate analysis of variance can be applied to more precisely assess a measurement system. For calculating a multivariate evaluation index, however, a limitation can be found with the geometric mean strategy. To estimate the multivariate evaluation index, no attempt was made to quantify the greater importance to the most significant pair of eigenvalues, extracted from variance–covariance matrices for process, measurement system, and total variation. Therefore, the aim of this research is to come up with solutions to this problem by adopting weighted approaches to estimate the multivariate evaluation index (Section 3). The problem statement in this paper has been raised while assessing correlated roughness parameters from the AISI 12L14 turning process (Sections 4 and 5). Due to distinct estimates among the multivariate indexes, the authors have also included more numerical examples from the literature to show how the new proposed indexes obtained better accuracy (Section 6). Based on the large data set analyzed, the authors concluded that the weighted approaches using the explanation percentages of the eigenvalues extracted from measurement system matrix were the most appropriate strategy for multivariate GR&R studies assessed by multivariate analysis of variance (Section 7).

2. Measurement system analysis by multivariate GR&R study

When reporting the result of a measurement of a physical quantity, it is required that some quantitative indication of the quality of the result be given to assess its reliability. Measurement Uncertainty is a term that is used internationally to describe the quality of a measurement value. In essence, uncertainty is the value assigned to a measurement result that describes, within a defined level of confidence, the range expected to contain the true measurement result [26,27]. AIAG [4] states that the major difference between uncertainty and the MSA is that the MSA focus is on understanding the measurement process to promote improvements (variation reduction). MSA determines the amount of error in the process and assesses the adequacy of the measurement system for product and process control. MSA applies statistical techniques to quantify process and measurement system components of variation. A general ANOVA model in MSA is represented by Eq. (1) [4,8,9,17,28]:

$$Y = X + E \tag{1}$$

In this expression, Y is the measured value of a randomly selected part from a manufacturing process, X is the true value of the part, and E is the measurement error attributed to the measurement system. The terms X and E are independent normal random variables with means μ_p and μ_{ms} and variances σ_p^2 and σ_{ms}^2, respectively. The mean μ_{ms} is referred to as the measurement system's bias. Typically, this bias can be eliminated by proper calibration of the system [9]. Thus, if it is assumed $\mu_{ms} = 0$, it can also be concluded that $\mu_Y = \mu_p$. If this assumption is violated, it will affect the estimation of μ_p but not the estimation of the variances. Since in a GR&R study the variances are of primary interest, the ANOVA model with p parts, o operators and r replicates can be expanded to Eq. (2) [6,7,17,29]:

$$Y = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \begin{cases} i = 1, 2, \ldots, p \\ j = 1, 2, \ldots, o \\ k = 1, 2, \ldots, r \end{cases} \tag{2}$$

In this expression, μ is the mean of the measured value (assuming $\mu_{ms} \cong 0$ and $\mu_Y = \mu_p$ as mentioned above), α_i is the